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Report on the B-Fields at NIF Workshop Held at LLNL October 12-13, 2015

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Executive Summary

A national ICF laboratory workshop on requirements for a magnetized target capability on NIF was held by NIF at LLNL on October 12 and 13, attended by experts from LLNL, SNL, LLE, LANL, GA, and NRL. Advocates for indirect drive (LLNL), magnetic (Z) drive (SNL), polar direct drive (LLE), and basic science needing applied B (many institutions) presented and discussed requirements for the magnetized target capabilities they would like to see. 30T capability was most frequently requested. A phased operation increasing the field in steps experimentally can be envisioned.

The NIF management will take the inputs from the scientific community represented at the workshop and recommend *pulse-powered* magnet parameters for NIF that best meets the collective user requests. In parallel, LLNL will continue investigating magnets for future generations that might be powered by *compact laser-B-field generators* (Moody, Fujioka, Santos, Woolsey, Pollock). The NIF facility engineers will start to analyze compatibility of the recommended pulsed magnet parameters (size, field, rise time, materials) with NIF chamber constraints, diagnostic access, and final optics protection against debris in FY16. The objective of this assessment will be to develop a schedule for achieving an initial B-field capability.

Based on an initial assessment, room temperature magnetized gas capsules will be fielded on NIF first. Magnetized *cryo-ice-layered* targets will take longer (more compatibility issues). Magnetized *wetted foam DT targets* (Olson) may have somewhat fewer compatibility issues making them a more likely choice for the first cryo-ice-layered target fielded with applied B_z .

Introduction

Achieving ignition of an inertially confined plasma is a national priority in the U.S. Three separate approaches are being actively pursued through international efforts in the field of high-energy-density research. These approaches are indirect drive hot-spot ignition (IDI), direct-drive ignition (DDI), and magnetized liner inertial fusion (MagLIF). Calculations show that an externally imposed magnetic field can help any of these three inertially confined fusion (ICF) approaches enhance their thermonuclear burn rates by (1) reducing heat conduction away from the assembled high-temperature plasma fuel, and (2) adding additional confinement to the charged particles from the fusion reactions thus enhancing their localized energy deposition in the cold fuel surrounding the central hot spot. Given the priority the nation has placed on ICF research, it was an appropriate and auspicious time to hold a workshop on the subject of magnetic field applications to experiments at the National Ignition Facility (NIF). For two days, researchers presented concepts and plans for experiments in a wide variety of scientific disciplines that would benefit from the ability to apply a magnetic field to a NIF target, and, equally important, to diagnose the interaction of the magnetic field with the high-energy-density states of matter created in the NIF targets. The first day of the workshop focused on applications to ICF, including the baseline IDI program pursued at NIF, the polar direct drive (PDD) program pursued at NIF, and areas where laser-driven experiments can help advance understanding of the processes in the MagLIF program being pursued at the Z machine at Sandia National Laboratories.

We gratefully acknowledge the excellent presentation by Fiksel on the performance of, and research areas pursued with the LLE MIFEDS system. Many good lessons were learned from LLE's development of the MIFEDS system, and many issues that are being faced as LLE plans to upgrade the MIFEDS system will also be faced at NIF with the deployment of B-field-generating coils in a NIF DIM.

Summary and Discussion

The agenda of speakers and discussion topics for the workshop is attached at the end of this document as a record of the meeting. The viewgraphs presented will be bundled together and distributed as the actual proceedings. The presenters at the workshop were asked to describe the requirements of the B-field appropriate for their experiments by defining 1) the field magnitude, 2) the volume magnetized, 3) the field onset or rise-time, and 4) diagnostic access.

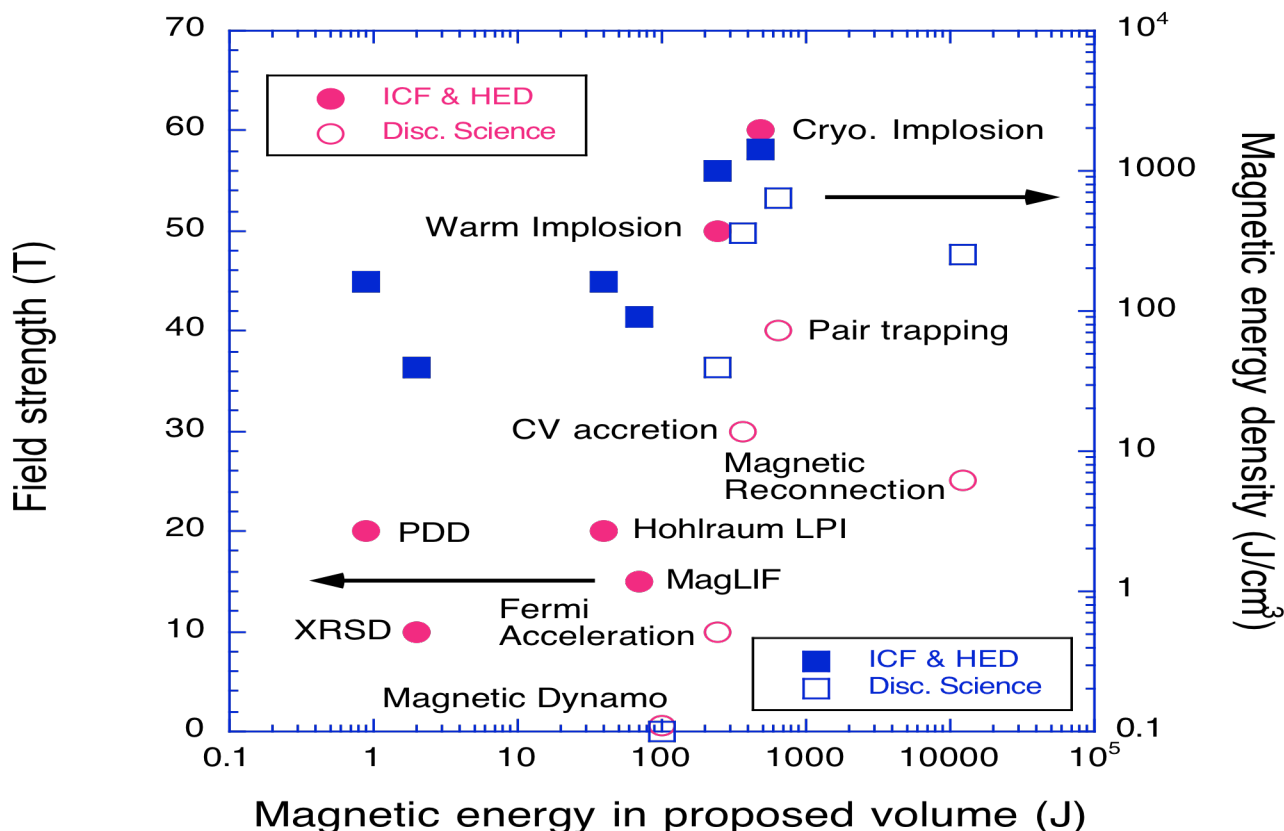


Figure 1— a collection of the proposed experiments that would use a B-field capability at NIF. The icons show (left axis, pink circles) the minimum requested field strength for “interesting” effects to be observed and (right axis, blue squares) the magnetic energy density over the volume of the proposed target. A shorthand label for each proposed platform has been written next to the corresponding pink circle. The horizontal axis is the energy in the proposed target volume for the given field strength. Target magnetized volumes have been estimated from the presentations given at the workshop. Filled symbols are proposed platforms that are consistent with on-going inertial-confinement fusion (ICF) and high-energy-density (HED) research at NIF, open symbols represent platforms proposed by members of the NIF Discovery Science community.

B-field Magnitude: Figure 1 shows a summary of the minimum requested magnetic field strengths for proposed experiments or applications that relate to ICF and Discovery Science research at NIF. The minimum field strength for interesting physics experiments is plotted versus the magnetic-field energy required to magnetized the proposed experimental volume (assuming completely homogeneous fields at the requested strength, which makes the quantity a likely upper bound). The right axis shows the magnetic energy density for the proposed experimental platforms, where the volume has been taken or estimated directly from the presentations at the workshop. In all of the ICF-HED cases the expectation is to use a magnetic-field-generating capability either completely internal to a NIF DIM or electrically coupled to a pulsed power source external to the DIM. All these initial concepts have requirements on energy and rise time that are not precluded by either system design. Most presentations at the workshop assumed an in-

DIM design that is similar to the pulsed-power-driven system currently being tested by LLNL's John Perkins and team. Generally speaking, all presenters who requested a pulsed-power driven magnetic field capability for their experiment reported that a field amplitude of at least 10 T is required to produce interesting and observable effects. Many platforms were shown to have greater benefit or even optimal configurations at higher field strengths ranging from 40T to 60 T. The result is that there is a great deal of commonality in requirements for a large subset of the presented experiments that would see the maximum benefit to a large set of users for relatively modest investment. The "common" field amplitude requirement for this set of experiments has a B-field strength in the range 20 – 40 T, although all reported that interesting physics can be observed at 10 T and some need >50 T for maximal effects. It is notable that at this time no one requested a B-field magnitude in excess of 100 T. It is our opinion that if fields of ≥ 100 T magnitude are demonstrated on NIF (using a laser-driven B-field coil for example) this will inspire several experimental proposals to utilize this type of B-field. The proposed experiments in Fig. 1 are roughly arranged in order of increasing experimental complexity from left to right based on when both the experimental platform and the requested capability at NIF may become available.

Experiment Details: Two points in Fig. 1 represent proposals to use gas pipe targets with an imposed magnetic field. These are the proposed experiment to enhance multi-keV x-ray emission (XRSD) from a laser heated underdense target presented by Kemp and Colvin, and a gas pipe experiment presented by Peterson and Sefkow to look at the effect of an imposed B-field on laser coupling to a cylindrical column of gas in support of MagLIF physics using the identical geometry to the 2004 NIF Early Light experiments. A cluster of four points between 20 and 40 T field strengths are split into two sets: The two ICF-relevant platforms include the PDD experiments with externally applied fields (Hohenberger), which assumes a small volume to be magnetized, and the investigation of the effects of an imposed axial B-field on hohlraum performance/hohlraum energetics (Strozzi and Montgomery) labeled Hohlraum LPI. The other two platforms in this range include one proposed by Koenig (Ecole Polytechnique, presented by Remington), to look at radiation-hydrodynamic accretion processes in x-ray binary or cataclysmic variable (CV) stars, and the other, proposed by Chen, to look for plasma effects in a population of electron-positron (matter-antimatter) particles trapped in an externally created magnetic field (labeled Pair trapping). These latter two proposals are part of the portfolio of Discovery Science (DS) experiments at NIF and will take significant engagement with the proposing teams to help define the experimental platforms.

The two highest-energy ICF-HED points in Fig. 1 require coupling of a magnetic field to a warm or cryogenic capsule implosion in a hohlraum. These points are notional and at the moment are not supported by any planned activities to bring the platform to the NIF or resources for engineering development. However, with that caveat, the kick-off presentation of the workshop by Perkins showed that in the regime of 40 – 60 T, cryogenic IDI implosions see a (very) significant enhancement in yield and a significant relaxation of the so-called "yield cliff" where capsule performance rapidly dies with increasing capsule surface roughness. The cryogenic platform has significant challenges over the warm platform. Thermal management of the capsule temperature and the shape of the ice layer that is formed on the inner surface of the capsule may preclude physical contact with a current-carrying coil to generate a B-field over microsecond timescales. The development of a thermally isolated field-generation capability adjacent to the shrouded cryogenic capsule is a major R&D undertaking that is currently not part of the on-going efforts to build a coil-driven B-field system as part of John Perkin's LDRD program.

Additionally, there are two points in Fig. 1 at low field strengths that will look at phenomena related to the origin of the highest-energy particles in the universe. These two DS platforms, the Fermi acceleration platform developed by Fiuza (Stanford) and the magnetic dynamo generation platform, developed by Gregori (Oxford) [presented on his behalf by Park] both require large target volumes (multiple cubic centimeters) to be magnetized, which again brings a host of challenges for the facility that have not as yet been evaluated in any detail. Finally, the last point in Fig. 1 is the Magnetic Reconnection point

representing the proposed DS experiment by Fox (Princeton) that requires moderate field strengths over very large volumes.

Magnetized Volume: The magnetized volume required by most of the experiments is typically 1 cm³ or less, which corresponds to the volume of an ICF hohlraum or a standard NIF gas pipe; the requirements on field-strength uniformity across the volume range from a stringent $\pm 10\%$ to $\pm 30\%$. Two experiments (Fermi acceleration and the magnetic dynamo generation) require 6 and 1200 cm³, respectively. The magnetic-dynamo platform uses a small B-field so that the total stored energy in the magnetized volume is still below about 2 kJ even for the highest energy-density case.

Field Rise Time: Proposed experiments that do not use any high-conductivity material in the magnetized volume can have a fast rise time for the B-field. In these cases the rise time can be set primarily by the design of the B-field pulsed power system. A 1 – 2 μ s rise time (or longer) is acceptable. Targets with high conductivity materials (Au hohlraum or Be gas-pipe for example) may require several tens of microseconds rise-time. This is principally determined by the time it takes for the field to diffuse into the target volume enclosed by a conductive housing (such as a gold or uranium hohlraum, a beryllium or aluminum shock tube, etc.). In addition, the mechanical forces experienced by the target due to the field diffusion must not significantly alter the experiment. As an example, a solid Be gas-pipe experiment designed for investigating laser propagation and absorption in high density, cryogenic D₂ (NIF collaboration with MagLIF) would require a rise time on the order of $\sim 50 \mu$ s in order to prevent the field from crushing the cylinder. Shorter rise times for MagLIF experiments might be enabled with horizontal insulating cuts in the conducting cylinder. Field rise-time considerations must include target design and current conductor considerations for optimization.

Diagnostic access: Diagnostic access in the hohlraum experiments can be achieved in a narrow region around the hohlraum mid-plane by using a “split-coil” design. This is the current plan for the magnetized hohlraum design proposed by Perkins and Rhodes. This provides adequate access for x-ray framing camera and neutron imaging measurements of the hot spot. Other experimenters proposed using a Helmholtz-type coil arrangement that would allow significant diagnostic access to the magnetized plasma region. In general, the scientists at the workshop felt that some capability to use different current paths, which provide some degree of flexibility in diagnostic access, was an important requirement for the NIF B-field system.

It should be noted that nearly all presentations at the workshop assumed the features of the DIM-based pulsed power system being designed by John Perkins and Mark Rhodes as a starting point for the various proposed experiments. It’s not clear how the proposed experimental designs would look different if the teams had assumed the cable-based externally driven system. For moderate field strengths as in Fig. 1, it most likely will make no difference to the experimental configuration. The system being designed by Perkins *et al.* assumes that all the stored energy to power the magnetic-field-generating coils is contained in an air box in a NIF DIM or TANDM, the new dual-purpose target/diagnostic manipulator. The entire pulsed power system is then placed inside of the NIF target chamber during use. This configuration limits accessibility and the maximum stored energy available but provides better performance. An alternative configuration places the stored energy outside the target chamber and transports the pulsed power through a DIM or TANDM via coaxial cables. NIF engineer Mark Rhodes prepared a draft report comparing these two options; the report is included at the end of this document. In summary: if the DIM power supply is configured outside of the target chamber and the power is transported with eight 50-ohm cables of 50 feet in length installed as a coil feed in a DIM or TANDM, the peak current capability will be 68% of the internal DIM-based power system if capacitor reversal is kept the same. Adding a second external capacitor increases the peak current to 83% of the DIM-based system. However, the system reaches the *Action to Melt* about 2 μ s after peak current. From a purely B-field performance perspective, low inductance, DIM-based pulser systems are best and will yield better performance than systems using external pulsers connected with cables. A DIM-based system increases peak field but stores the energy inside the DIM, a potential machine safety issue. A cable-based system restricts the highest fields

obtainable (still good for most applications) but removes the energy storage to outside the Target Chamber, reducing machine safety concerns. One outcome from the workshop is to look at this trade-off more rigorously (see action items below).

Engineering and resource considerations: We note that the experiments proposed in Fig. 1 above are not yet “resource” loaded and does not imply when a capability may be realizable at the NIF, or even where the break points are where the facility’s ability to support the integration of the platforms into the facility infrastructure is out of scope. That said, it is critical to tie the benefits of magnetic-field capability at the NIF to the National Program for achieving a burning fusion plasma. If the benefits for fusion research were made clear, or if “mainline” ICF research seems to stall following approaches without an externally imposed magnetic field, then the required conversations about resources and priority become much more urgent and focused. At the workshop, all three of the current “mainline” ICF approaches were represented in presentations that made the case that preliminary calculations show modest-to-large enhancements in plasma temperature and fusion-product deposition heating as a result of imposed axial magnetic fields. In two of the platforms, IDI and MagLIF, the simulations show the potential benefits of an external magnetic field capability were very significant and potential “game changers” with respect to the probability of achieving modest to large gains. While (as written above) nearly all presentations made the case for interesting (new) physics results for fields in the 10 to 30 T range, it was clear that the real requirements on field strength, field rise time, the field “soak” time for IDI targets in conductive enclosures (i.e., hohlraums), and what, ultimately, would be the volume over which uniform (high) field strengths would be required will be more stressing than what was presented. A problem with the capabilities currently under development in Perkins’ LDRD-funded effort is that while they may provide “early-look” interesting physics, it is not clear that they will satisfy the ultimate requirements necessary to enable robust, high-gain fusion reactions for the IDI and MagLIF platforms. More to the point, what is currently under design is simply a capability, and the work necessary to integrate the capability with the facility, to perform the systems-engineering analysis to make the capability a robust and routine part of operations, and the resources to support and procurements or physical modifications necessary to implement the capability have not been discussed. We also expect that initial magnetic field experiments will reveal additional engineering and physics issues that may require design and requirement updates. A goal of this workshop is to generate a plan from the NIF Target Experimental Systems organization to integrate various levels of capability into the facility. Based on the strong response of the scientific community to this workshop, we are putting resources into this problem in FY16. A result of developing a resource-loaded plan will be identification of “breaking points” where the work required for integration of a specific design is not achievable without a national conversation about allocating resources.

Laser-generated B-fields: Not all experimental platforms presented at the workshop require external fields to be generated with cylindrical coils driven by a pulsed power current driver in the DIM. Moody presented recent results from Fujioka (ILE, Osaka University) and Pollock that measured laser-generated B-fields with field strengths in excess of 600 T. Experiments proposed that would benefit from using a laser-generated B-field capability are discussed now. The type of foil target described in the work of Fujioka and Pollock could be adopted from the LFEX or OMEGA geometries to a NIF geometry potentially in a few years time with dedicated effort. It seems likely that the bent metal foils and metal loops used for laser-generated B-fields can easily be made to accommodate the cylindrical geometry of the x-ray source target and MagLIF target already described in Fig. 1. Thus, those two proposals could evaluate designing a laser-generated-B-field into their experimental platform. This is likely possible in the next few years with dedicated design effort. The field strengths reported for the laser-driven targets at LFEX and EP are much greater than the 10’s of Tesla identified as appropriate for seeing effects in the x-ray source target and MagLIF targets. Similarly, the rise time and duration of the laser-generated fields are much shorter than what was investigated computationally for the x-ray source target and MagLIF targets. Finally, there is a magnetic reconnection experiment proposed by Fox (Princeton) that would look at the reconnection rate, geometry of current layer and transition to a fully turbulent reconnection

regime in the plasma generated in the blow off from two opposed, laser-irradiated plastic foils. The field strength of interest to Fox *et al.* is on the order of 30 T. While relatively modest in field strength, the complexity of that laser-generated-B-field platform would require several years to fully develop.

Facility Concerns

Bruno Van Wonterghem presented the issues of concern to the NIF facility that come with efforts to implement a B-field capability at TCC; the successful implementation of B-field capability on NIF will be an iterative process between the facility, NIF expert groups and the user community. Critical to achieving success will be having a crisply defined set of requirements of any use case. Already, we've described above the trade study that the facility has agreed to undertake to look at the costs and benefits of systems that have the stored energy for to drive magnetic-field coils either internal or external to the DIMs. Additionally, clarification of whether the laser-target and the field coils should be integrated on the same positioner or introduced to the chamber on separate positioners (as with the MIFEDS system at OMEGA) needs to be evaluated within the constraints of the NIF target positioning and alignment scheme. The NIF Target Experimental Systems Engineering organization will take the lead on producing these trade studies in the short term.

One set of issues that Bruno highlighted that must be understood include clearances: 3 ω light - B-field equipment must maintain driver beam stay-out zones; 1 ω light - B-field equipment must maintain unconverted light stay-out zone or implement laser shielding in impacted area; B-field equipment must clear required diagnostic lines of sight; and B-field equipment must be able to be aligned, i.e., must fit within the Target Alignment Sensor (TAS) jaws. The set of issues with respect to debris and shrapnel was also emphasized: implemented designs must reduce additional debris and shrapnel to protect optics and diagnostics. As guidance, system designs should minimize coil mass (to less than ~ 0.5 mg), and should make material selections consistent with NIF cleanliness and outgassing specifications. The facility would prefer a system design that vaporizes the coils in order to reduce the overall debris mass that could turn into damaging shrapnel. A strong recommendation to come from this workshop is that NIF groups working on implementing a B-field system in the NIF chamber collect existing data on in-chamber debris from the OMEGA (and ORION) laser systems, as well as do tests and characterizations offline, to determine how debris distributions may result in the NIF target chamber. Safety at NIF is always paramount, and that applies to personnel safety and machine safety. The facility emphasized during the workshop safety issues that will affect designs: provide stored-energy containment and safety, electrical stored energy and capacitor failures do need to be entirely contained inside the magnetizer enclosure with no possibility for release in the target chamber; electrical safety requirements need to be met for handling/servicing in the Target Bay. Any design will need to be consistent with facility radiological controls and be cognizant of issues relating to the activation of materials in NIF's radiation environment: entrant magnetizer and coil systems need to be decontaminated/released (similar to snouts); expert groups will need to evaluate activation for use in yield experiments. The cleanliness steering group will need to evaluate unusual or new materials.

The details on these issues and many more are in the charts Bruno presented (included as the proceedings of this workshop). Actions that came out of the facility presentation include:

- The need to perform a Failure Modes Effects Analysis (FMEA) with respect to stored energy containment and electrical safety
- Evaluate design choices: magnetizer pulsed power cables (what are limits); switch/trigger requirements (optical versus electrical), etc.
- Evaluate transient impact on alignment by the effects of the magnetic fields and pulsed currents
- Ensure the EMI/EMP created by the magnetic field generator and coil do not perturb the diagnostics or other sensitive equipment

- Evaluate the design trade offs between field strength, coil supports and amount of debris, and analyze debris data from other facilities using magnetic field target
- Generally, partner with users to ensure that user requirements as implemented in whatever B-field generating system is designed are compatible with facility requirements for safety and laser-system performance.

Conclusion

A workshop on the science that would be enabled by having an externally applied magnetic field capability at the National Ignition Facility was held at Lawrence Livermore National Laboratory October 12th and 13th, 2015. 30T capability was most frequently requested. A phased operation increasing the field in steps experimentally can be envisioned. It is clear from the discussion that took place that it is critical for the NIF facility to perform an in-depth analysis of the proposed capability for sets of requirements. For applications that require field strengths >30 T, a trade study needs to be performed between systems completely contained within the NIF DIM/TANDEM and a system with the stored energy outside the DIM/TANDEM coupled to an extensive, possibly custom, cable plant inside the DIM/TANDEM. It was acknowledged by all at the workshop that implementing field capability for warm targets, or doing experiments with laser-generated fields will be much simpler than implementing a system for cryogenic targets. Of course, cryogenic targets are the highest leverage for increasing the areal fuel density and alpha particle energy deposition in implosions, so emphasis should be placed on designing a system to impose an axial magnetic field on a cryogenic capsule in a hohlraum.

The most salient outcome of the workshop, however, is that the separation between physics teams conceptualizing experiments and the facility developing the B-field capability needs to be bridged. In particular, a LDRD funded capability-development effort is currently designing a pulsed-power system offline in a laboratory. As a result of the workshop, there is a commitment to work on a plan to integrate that capability with the NIF DIM/TANDEM systems, with the NIF timing and integrated controls system, including data archiving, as well as to plan an effort to integrate the hardware being tested with the facility's transport and handling protocols, with the facility's material compatibility constraints, and to perform the required safety analysis. Resource-loaded plans are necessary to implement a MIFEDS-like magnetic field capability at NIF in order to make essential progress in a number of areas of HED science. The plans will have to identify for a given capability what scope can be accommodated and what is a breaking point beyond which the facility cannot support without significant change in budget and schedule.



Workshop attendees at the B-Fields at NIF Workshop, October 12-13, 2015 at Lawrence Livermore National Laboratory.

Appendix 1 - Action Items

The following are notes that either have direct action items, or the seed of an action to be pursued by the proper subject matter expert. These items were recorded directly in a notebook during discussion sessions in the workshop.

Program Actions:

- Bedros Afeyan points out need to do Fokker-Planck simulations to explore B-field effects on non-local heat transport (Action to D. Montgomery and D. Strozzi)
- For MagLIF experiments diagnostic access to the axial dimension of the NEL gas pipe; John Perkins suggests Mark Rhodes will look into designing some Helmholtz coils that will generate a 30T field and accommodate a 4 mm dia. x 7 mm length gas pipe (Action to M. Rhodes)

Facility Actions:

- NIF facility will need to get the historical data from LLE on the actual distribution of debris from MIFEDS coils on OMEGA and EP optics and diagnostics. (Action to P. Arnold)
- Perform a high-level trade-off study of payload in DIM (which provides a fast rise time) versus external power supplies (ease of access; requires stiff, bespoke cable runs). (Action to J. Moody and P. Arnold)

Appendix 2 - Closing Comments

- John Moody – The striking feature of the discovery science (DS) experiments is the large scale of what they’re proposing.
- Bruce Remington – What do these DS proposals (concepts really) mean for the facility? Contrast what is being put forward with the seven years it took to bring the EPEC platform on line. (KBF: they are of very nearly equal complexity.)
- Hye-Sook Park – The NIF facility needs to support scoping (not reviewed/approved/scheduled) experiments with LPI simulations and assessments. [She’s saying DS teams don’t have the support necessary to bring up new platforms at NIF.]
- Fiuza – Large-scale volumes should be feasible in 2 to 3 years time frame just by scaling up Perkin’s LDRD configuration
 - Concept proposed by Fiuza requests 10T field over a 6 cm^3 volume, which would allow imaging over 20 Larmor radii, which lets you see Fermi acceleration. This design is very ambitious and only long term. (Action to Fiuza’s team to work on such a design in order to sharpen facility requirements)
- Bruce R./John M. – What is the biggest facility issue? Likely debris and machine safety (stored energy).
- Kyle Peterson – What’s the relative importance of cryogenics? Is the best approach to push on a warm system and defer development of the cryo system later?
 - John Perkins – in response to Kyle P.: yes – develop cryo in parallel with deploying warm capability in short term.
- Grant Logan – Cryogenic layered targets have much more stringent requirements than the cryo gas targets for MagNIF and MagLIF. Room temperature MagNIF and MagLIF would be an easier (a good place) to start.
 - Need a strategy and organization for the (complicated) design of a B-field system to interface with a cryogenic fuel layered targets; this is outside the scope of Perkin’s LDRD. (challenge from Grant Logan to ICF program)
- Mike Campbell – NIF supports all three viable ICF approaches -> MagLIF is the only application that programmatically requires (not just “is helped by”) a B-field. It is good to put at the front of the queue a mission-driven need.
- Gennady Fiksel – Two different fields, 20T versus 50T might require outside-the-DIM energy storage. Part of the trade design study to settle on initial capability: go for 50T and operate at 20T, or design for 20T and work later to build to 50T.
- Bedros Afeyan – Today’s talks focused on measuring the B-fields, including proton radiography and other techniques (such as Zeeman splitting). This issue presents big requirements on any systems that is designed too (i.e., diagnostic access).
 - Designers and plasma HED physicists should look at the effects of Zeeman splitting of high-n lines for local B-field measurements. Steven Ross – this is starting to be looked at at Janus; maybe the $E/\Delta E \sim 10^4$ is an insurmountable challenge?
 - Following discussion of reconnection experiments by Will Fox, John Perkins notes that converging of the axial field for ICF in the hotspot with residual kinetic energy twists field lines into toroidal islands. This needs to be looked at in LASNEX.
 - J. Giuliani – We will need dedicated experiments to look at the significance of the Nernst term in the Braginskii’s plasma transport equations.
 - KBF – left out of the discussion is the impact or benefit of Thomson scattering in the presence of magnetic fields. Should be included in trade studies.

Appendix 3 - A quick look at Magnetized NIF targets using a cable feed (by Mark Rhodes, LLNL)

Case	Description	Peak Current (kA)	Time to peak (μ s)	Temp at peak ($^{\circ}$ K)	Specific Action @ peak $\text{Amp}^2\text{s/mm}^4$	R_{series} (Ω)	Reversal (%)
1	Baseline, 1 ICAR cap at 40 kV, no cables, i.e. DIM based	73.5	1.84	502	2.90×10^8	.2	28
2	1 ICAR cap with eight 50 foot 50 ohm cables	58	2.8	497	2.90×10^8	.2	45
3	Same as #2 but less reversal	50	2.67	420	2.14×10^8	.34	28
4	Two ICAR caps	61	3.35	585	4.0×10^8	.34	N/A

Summary: Assuming eight 50-ohm cables each being 50 feet long can be installed in a DIM or TANDM as a coil feed, the peak current capability is reduced by 68% if capacitor reversal is kept the same. Adding a second capacitor increases the peak current to 83% of the DIM-based system but reaches the Action to Melt about 2 μ s after peak current.

Discussion: As part of the Magnetized NIF LDRD, we are designing a higher energy version of the LLE MIFEDS systems where a charged capacitor is housed within a DIM (or TANDM) and would be connected to a hohlraum coil via a rigid, low inductance, short as possible, parallel plate transmission line. If this design ends up being considered too risky, it is possible to consider putting some level of capacitor bank outside of the target chamber and route flexible cables through the DIM to feed the coil.

To get a sense of how using cables would affect the performance of a magnetization system, I have compared several cases using PSPICE. I made the following assumptions. We would use eight 50-ohm cables. Since the voltage limit on our present capacitor is 40 kV, the cables could be RG213 sized cables which are about 0.4 inches OD each.

The table above shows the results of four different cases. Case 1 is the baseline, DIM-based, design where a single ICAR capacitor (4 μ F at 40 kV) is mounted as close as possible to the target inside a DIM air box. This baseline case can, in principle deliver up to 73.5 kA to the baseline coil design (233 nH). Note that we have to date only operated the baseline coil to 60 kA which produced 58 Tesla peak field. Actual coils on real NIF shots look to be slightly bigger ID and will require a center gap between coil-halves so peak B-field per amp will be less than with the prototype coil.

For Case 2, I simply added 500nH of inductance between the same pulser and the coil. This is approximately the inductance of eight 50-feet long 50-Ohm cables in parallel. This reduces the peak current capability to 58 kA or 79% of Case 1. This would still produce over 50 Tesla in the baseline coil. However, note that the capacitor reversal increases from 28% to 45%. At 28% we are already pushing the suggested limit of 20% reversal. The coil temperature and action at peak current are about the same as Case 1 so we are only pushing the capacitor reversal.

For Case 3, I increased the series damping resistors to keep the reversal fixed at 28%. This further reduces current capacity to 50 kA or 68% of baseline. Coil temperature and action are a little lower than baseline which makes sense since the current and time to peak are reduced from Case 2. 50 kA would still produce fields in

excess of 40 Tesla as long as the center gap between the coil-halves doesn't get too big. Generally, this would still be a significant system but doesn't meet the LDRD requirement for 50T and there is little or no design margin left for larger volumes, "roomier" coils, or bigger center gaps.

For Case 4, I attempted to get back some of the peak current and/or design margin by adding a second ICAR capacitor for a total of 8 μF . This gets us back to 61 kA. However the coil temperature at peak current is higher and the coil reaches "action to melt" about 2 μs after peak current. Until we test a coil at these conditions, it is unclear if the coil would actually reach the predicted peak current before internal disassembly. The PSPICE model does not account for any issues due to magnetic forces and we know that our faster, prototype pulser coils are disassembling internally just after peak current at the 60 kA level with a 1 μs time-to-peak. I expect slower pulses (long time to peak) will exacerbate the mechanical disassembly issue.

There are many other possible combinations of cables and capacitors and voltages but these four cases illustrate the general trends. The extra inductance tends to lower the peak current, increase "time to peak" and increase reversal. Adding capacitance recovers some of the peak current but the slower pulse pushes the action higher and probably puts the coils more at risk for force related damage before peak current is reached.

One possible direction would be to lower the capacitance and increase voltage. A 2 μF capacitor at 60kV would deliver 59kA in 2 μs with an action of only 2.02×10^8 , but the reversal is back up to 40%. This might also require a bigger size cable to handle the higher voltage.

Conclusion: From a purely B-field performance perspective, low inductance, DIM-based pulser systems are best and will yield better performance than systems using external pulsers connected with cables. LLE has set a precedent for fielding DIM-based pulser systems are only considering external, cable connected systems because they don't have enough room in their TIM's for a higher energy system. A DIM based system would yield better B-field performance than an external, cable-fed system as long as it can be engineered to assure the safety of the NIF system.



B-Fields at NIF Workshop
Monday-Tuesday, October 12-13, 2015
Agenda
B481 R2004/2005

Monday, October 12, 2015, B481, Room 2004/2005

1:00 p.m.	Introduction	M. Herrmann/D. Larson
1:10	Charter and Charge	K. Fournier/J. Moody
1:15	ICF Needs for Ignition Applications	J. Perkins
1:45	Discussion on ICF Requirements and Impact on ICF	
2:15	ICF Hohlraum Preformation/LPI Suppression	D. Strozzi/ D. Montgomery
2:45	Discussion on ICF Requirements and NIF Implementation	
3:15-3:30	Break	
3:30	X-Ray Sources	J. Colvin/E. Kemp
3:50	MagLIF	A. Sefkow
4:20	Requirements regarding laser-heated plasma/ Discussion of NIF Implementation	
4:50	Direct Drive: PDD and Shock Ignition	M. Hohenberger
5:10	MiFEDS at OMEGA	G. Fiksel
5:40	Discussion regarding implementation issues	
6:10	Facility and Machine Safety Issues	B. Van Wonterghem/D. Kalantar
6:40	Summary	All
7:00 p.m.	Adjourn	

Tuesday, October 13, 2015, B481, Room 2004/2005

8:00 a.m.	Gathering and Refreshments	
8:30	Accretion Processed in Astrophysics	B. Remington/M. Koenig
8:50	Collisionless Shocks: PIC Simulations of MiFEDs Experiments	F. Fiuza/A. Spitkovsky
9:10	Fermi acceleration	H. Park/G. Gregori
9:30	Discussion Regarding Laboratory Astrophysics	
10:00-10:20	Break	



Tuesday, October 13, 2015, B481, Room 2004/2005

10:20	B-Field Generation at LFEX	J. Moody/S. Fujioka
10:40	Reconnection	W. Fox
11:00	Discussion on Plasma Physics	
11:30	Positron Trapping	H. Chen
11:50	Discussion of Contributed Topics	
12:30	Wrap Up	
1:00 p.m.	Adjourn	

Host: Kevin Fournier, 925-423-6129
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